Management strategies for an input controlled fishery based on the capture of short-lived tropical species: the example of Australia's Northern Prawn Fishery

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Statement of Originality

I declare that this thesis is my own work except where duly acknowledged. It contains no material that has been accepted in any form for another degree or diploma by the University of Tasmania or any other institution. To the best of my knowledge and belief, no material within this thesis has been published or written by another person except where due acknowledgement is made in this declaration or in the text of the thesis.

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Declaration

This work originates mainly from a paper submitted to the Northern Prawn Fisheries Advisory Committee (NORMAC), an invited chapter to a book, and two collaborative projects. It is therefore necessary to declare my contribution and those of my co-workers in this thesis.

Chapter 1 is the product of a multi-authored paper to be published as a chapter in a book edited by T.R. McLanahan and J.C. Castilla. I am the first author of the book chapter and initiated, co-ordinated and led the development of this chapter. However, each author has been the first author of certain sections. In addition to leading the development of this Chapter, I wrote the abstract, the historical perspective of the fishery, the sustainability of target species and the summary. Neil Loneragan wrote the section entitled 'A complex ecosystem in time and space', and Dave Brewer wrote the section 'Prawns are not the only catch'. Everyone has contributed to edits.

I am the sole author of Chapter 2 which started as a document I submitted to NORMAC and then developed further for this thesis.

Chapter 3 onwards are the results from Dichmont *et al.* 2001 and Dichmont *et al.* 2005. For both these projects I was the Principal Investigator; I therefore obtained the funding (in the case of Dichmont *et al.* 2005), managed the project, determined the contents of the research, developed or supervised the methodology, undertook most of the write-up and edits, and undertook the communication. Some of the chapters refer to Dichmont *et al.*

(2003a), which is one of the published outputs of the FRDC project Dichmont *et al*. (2001). I am the first author of this paper and I have included this publication as Appendix 1 rather than simply copy the equations of the assessment model and its description from the publication into this thesis. Chapter 4, 5 and 6 are the product of a collaborative 3 year project entitled "A new approach to assessment in the NPF: spatial models in a management strategy environments that includes uncertainty" by Dichmont, C.M., Deng, A.R., Venables, W.N., Punt, A.E., Haddon, M. and Tattersall, K. and referred to as Dichmont *et al*. (2005). These chapters have been written up as 3 consecutive papers. I am the first author of each of the three papers to be submitted to Fisheries Research. Additional scenarios not in the papers are in Section 6.8. Appendix 2 is written by my supervisor Bill Venables and is added for interest only.

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CONTENTS

INTRODUCTION AND SUMMARY

Rationale and Thesis Structure

Input controlled fisheries for short-lived species are common but the management options available are rarely examined in great detail. The Northern Prawn Fishery (NPF) of Australia is a very valuable industry and has a relatively long history. The extent of previous research and the value of the fishery mean the NPF provides an excellent opportunity for exploring alternative management strategies for a fishery on input controlled short-lived species.

I start this thesis with a description of the fishery and its management (Chapter 1). It is not a complete analysis of the all the aspects of the partnership approach. An equally fascinating story on the personalities within the partnership approach and how they shaped the history of this fishery is not included. Included is a discussion of the achievements in the Northern Prawn Fishery (NPF) partnership approach that has relied on co-management by managers, scientists and the industry. These achievements include:

(a) the scientific discovery of the prawn life cycle and its reliance on coastal habitat produced a series of protected areas formulated and supported by all these parties,

(b) assessment of the sustainability of tiger prawns has resulted in very controversial and large effort reductions over several decades, and

(c) research on bycatch in this fishery is more advanced than many others in the world mainly due to the proactive nature and support from the industry.

The next section (Chapter 2) broadens the scope beyond the NPF by describing the management and assessment process of some key short-lived species, with many from Australia. Here, I define a short-lived species as being animals that grow to a maximum of 3-4 years in age. A further criterion for choosing these examples is that they undertake at least some basic management such as limited entry and total effort/catch control. Interestingly, an array of management systems are applied across the range from using mostly input controls to mostly output controls, including mixtures of the two. Excluded are the vast bulk of fisheries that rely on short-lived species with little or no management. This is not intended as an exhaustive list. I have chosen examples that have direct relevance to the NPF as comparisons or contrasts. In these cases many of the methods and conclusions from this study are applicable to these fisheries and vice versa.

Chapter 3 details the Management Strategy Evaluation (MSE) process itself (in the context of the NPF) and the most well known examples of its use. A key graph (Figure 3.1) should help the reader keep track of the remaining method sections that follow. Since this field is rich in terminology but also does not have consistency, a description of the terminology used in this study is provided in Section 3.1.

Historically, the official assessments of tiger prawns in the NPF did not forward project the assessment beyond a simple process to investigate different management options. In Dichmont *et al*. 2001 and Dichmont *et al* 2003a (Appendix 1) simple harvest strategies and a risk analysis are undertaken. As a major upgrade to the methodology, this thesis uses a much more sophisticated approach; Management Strategy Evaluation (MSE). This has never been applied to this fishery before and, for prawns, has not been applied using a fully stock structured operating model. Indeed the only other prawn application that has been reported (O'Neill *et al*. 2004) is applied to Queensland and Torres Strait Island prawn fisheries, and developed an operating model at very much the same spatial and temporal scale as the Base Case management strategy. In this PhD we use one of the major strengths of the MSE methodology which is that it permits comparisons of alternative assessment assumptions. We used MSE to test the simplification assumptions in the NPF assessment (e.g. single versus multi-stock) and to determine the effect of incorrectly parameterising the assessment relative to the operating model (e.g. high fishing power in one with low fishing power in the other).

The operating model, which represents a virtual resource being managed, is described in detail in Chapter 4. The particular operating model in this MSE is new and mathematically describes a multi-stock and multi-species tiger prawn resource, but also includes effort directed at banana prawns. These are key aspects of the fishery and are a major change from past analyses in the NPF. In most instances, stocks are assumed to be biologically independent of each other. This is the worst case scenario i.e. if one stock is over-fished, it can not be supplemented or replenished by neighbouring stock regions. However, an option to include environmental influences that affect more than one stock is also included in some scenarios. This required an analysis of the between stock covariance structure of the recruitment estimates and is new for the NPF.

As part of the MSE process (Chapter 5), one needs to describe the whole management system and include all known sources of uncertainty; from data collection, to assessment, setting the effort levels, and implementation of management decisions (see Chapter 5). The determination of the implementation errors entailed a detailed analysis of past decisions made by the managers of the fishery and highlights a key source of uncertainty within the management process. This is a new way of looking at management successes and failures in the NPF and has shown that a good management procedure can be thwarted by implementation error.

Three different stock "assessment" methods are included in the MSE (Chapter 5). These are a simple linear regression of annual catch rate against time, a biomass dynamic model and the delay-difference model (called the Deriso model in this thesis, described in detail in a paper published in Fisheries Research, and included as Appendix 1). The spatial and temporal scale (as well as complexity) is markedly different among these three approaches. A weekly delay-difference stock assessment was first formulated by Dr Andre Punt and applied to the Northern Prawn Fishery (Punt 1996), but is further refined and tested in Appendix 1. Until this application to the NPF, delay-difference models were applied with a time step of one year (e.g. Schnute 1985). However some changes were made to the original Deriso model of Punt as described below.

An interesting aspect of this application of a delay-difference model to a short-lived species is that an individual recruiting into the fishery may also be contributing to the spawning population at the same time. This means that the "delay" in the delay-difference equation of the model takes on a specialized meaning, another unusual aspect of the method. Why then use a delay-difference model? The underlying reason is that we are trying to keep track of some aspects of the age structure within the population; mainly because there has, in the past, been some dispute as to whether prawns have a defined stock and recruitment relationship and also that many reference points rely on knowing the parameters of the stock-recruitment relationship. As is common for a crustacean, age structure data is not available. Sadly, any long term size structure data is also not available which makes it impossible to directly estimate a full age/size structure tuned to data. Although there is a fully age structured assessment developed for the tiger prawn species in the NPF by using the von Bertalanffy growth equation (see Wang and Die 1996 and Dichmont *et al*. (2001)), the delay-difference model described in Appendix 1 provides very similar results (to within 4 decimal places) to this age structured model, but is much quicker to run (something that is essential in a Management Strategy Evaluation framework). The main reason for this similarity is mathematically obvious, since both methods as applied to this fishery assume knife edged selectivity and use the same data source.

This fishery can be classified as relatively data poor, because no long-term fishery-independent monitoring data is available. This means that many parameters are being estimated from the same data sources, which complicates the analyses and causes serious confounding. Much of the discussion on this confounding occurs within the estimates of fishing power, which does not form part of this thesis ("effort creep" constitutes a major management problem in this fishery). Most of this debate and methodology is described in Dichmont *et al*. (2003b) and is used here as an input. Since the model suffers from data paucity, the process of assessment is unusual:

(a) firstly, annual recruitment parameters and spawning indices are estimated using catch and effort data together with estimates of catchability and fishing power input to the model, and

(b) given these parameter estimates, the stock-recruitment parameters are estimated. Since prawn recruitment success can be strongly affected by the physical environment, there is also an underlying set of temporal autocorrelation parameters about the estimated stock-recruitment relationship. In (a), no underlying stock-recruitment structure is assumed; each year's recruitment is assumed to be independent of the next. Only in stage (b) is there an investigation of whether these estimates follow a stock-recruitment pattern. Given that the recruitment values are estimated in a separate process, the precision of these variables needs to be carried into the stock-recruitment estimation process. This is done through modifying the likelihood to include an asymptotic variance–covariance matrix obtained by fitting the population dynamics model in part (a). The estimation of the stock–recruitment relationship therefore takes account of the relative precision of the annual recruitments and the impact of (correlated) environmental variability in recruitment; this was a novel modification to the NPF assessment first presented in Dichmont *et al*. (2003a).

Wang and Die (1996) applied an innovative twist to their age structured model, which directly acknowledges the technical interactions between the two tiger prawn species that are caught i.e. there are almost no occasions where only one species is caught. The single species approach, if not modified, would grossly overestimate possible sustainable effort on a species if the “bycatch” of another species is not considered. In the Wang and Die (1996) model, they address this through calculating fishing mortality as the sum of effort applied to the target species and effort applied to the ‘bycatch” tiger prawn species. Of course, this requires using two forms of catchability; a target and a “bycatch” (they use the phrase “bycatchability”) parameter. However, they did not extend this concept beyond this fishing mortality equation, which means that their calculation of the effort levels required to reach the Maximum Sustainable Yield (E_{MSY}) for each of the two species can not be simply added together as an estimate of the total E_{MSY}. As a result, in the delay-difference model described in this thesis the concept is extended to be included in future projections and in the calculation of the reference points (this complicates the mathematics of the model somewhat and is described in Appendix 1).

The successes (and failures) of the different Management Strategies are analysed in Chapter 5. It should be borne in mind that each Management Strategy includes the assessment process as well as the set of decision rules used to determine effort levels. Here the key issue was the appropriate spatial and temporal scale of the Management Strategies as well as their mathematical complexity. Options include annual versus weekly time steps, single versus multi-stock assessments and/or decision rules, different assessments, inclusion of age structure.

Designing an experiment to determine the key factors to which the MSE performance measures are sensitive is not new, but is rarely applied in fisheries simulation modelling. I suggest that the two stage process undertaken in Chapter 6 has been an excellent compromise between undertaking a comprehensive sensitivity test and minimising computer time. The first stage involved undertaking a statistically unbalanced experiment (thereby reducing the number of scenario runs to something more feasible in terms of computer time). The results from the unbalanced design were used to identify the key factors, which were fully tested using a statistically balanced design process. Chapter 6 therefore investigates the factors that are most influential to the Performance Measures and uses a range of different operating model arrangements and management strategies. In many cases, the mismatching of assumptions between the operating model and management strategy was the most revealing of relationships and interactions. A few extra scenarios are described in Section 6.8 as an Appendix for completeness. They were excluded from the main part of the chapter purely to keep it to a reasonable length.

Finally, the study recommends future directions of management and research (Chapter 7). References occur after each chapter. The overall summary is in fact next.

Summary

The NPF is one of the Australian Commonwealth's most valuable fisheries. The species groups targeted include tiger, banana and endeavour prawns. The fishery is managed using input controls and, from 2001 until 2004 (the period which spans this study), the agreed target was for the level of fishing effort expended to lead to a 70% chance (or greater) that the spawning stock size of tiger prawns was at or above that corresponding to Maximum Sustainable Yield, S_{MSY}. A key issue in the management of this fishery is that the efficiency of fishing effort is continually increasing so that past effort reductions have been fully offset by improved efficiencies. In fact, some past effort reductions did not actually lead to a real reduction in effective effort. As a consequence of this, there was no recovery in the size of the tiger prawn resource but rather, in some years, a decline, until a major effort reduction program was implemented in 2001.

Early stock assessment methods for tiger prawns were limited to simple models (e.g. equilibrium surplus production models - Somers (1990)) with limited goals. More recent assessments were based on the population dynamics model developed by Wang and Die (1996). This model operates at a much finer (weekly) time-step, specifically includes growth and recruitment, and separates the two tiger prawn species. The assessment technique based on this model was evaluated and improved by a FRDC-funded project (Dichmont *et al*. 2001) which produced two assessment techniques: a) a modified version of the Wang and Die method, and b) a new method based on a Deriso-Schnute model (Dichmont *et al*. 2003a). A non-equilibrium, non-linear, biomass dynamic model with an annual time-step using tiger prawn data only was developed by another FRDC-funded project (Haddon and Hodgson 2000). The biomass dynamic and Deriso-Schnute models produce somewhat different outputs, but both suggested in 2001 that the tiger prawn resource was depleted and well below the biomass that could produce MSY. Both models

assume a single homogenous stock of tiger prawns in the NPF, although when fitting the biomass dynamic model, the catch and effort data used are standardized with respect to geographical location and week in the season to make some allowance for spatial heterogeneity.

Spatial stock assessments would appear to be essential for a resource that tends to aggregate, or that has distinct geographical trends in abundance or availability. Die *et al*. (2001) suggested that there are several distinct stocks of tiger prawns in the NPF and that assessment methods should be applied at a finer spatial scale than had been the case in the past. Dichmont *et al*. (2001) attempted to conduct stock assessments for tiger prawns in the NPF by "stock area", but the calculations took a long time and were highly uncertain. The preliminary results of these spatial assessments suggested that some stock areas were highly depleted with spawning stock sizes much lower than suggested by the single-stock models.

Dichmont *et al*. (2001) and this study also assessed the magnitude of error in the estimate of the effort corresponding to MSY (E_{MSY}), and other parameters on which management advice is based. This error was caused by uncertainty in the data and in the values for some of parameters of the assessment model that are specified using auxiliary information rather than being estimated from the catch and effort data. In brief, the error bounds on the estimate of E_{MSY} were very large, implying that E_{MSY} was unlikely to be the best guide to good management in the NPF.

The findings from Dichmont *et al*. (2001) and Die *et al*. (2001), coupled with the transition in August 2000 of the fishery from management based on A-units to management based on gear-units, made it important that more realistic fishery sustainability targets needed to be identified. Specifically, there are indications that the present management targets, coupled with stock assessments applied at large spatial scales, may not be sufficiently precautionary and that serial or local depletion may not be prevented.

It is unknown whether the apparent failure of the NPF tiger prawn stocks to recover during the 1990's was related to limited management options, serial depletion of stocks (Die *et al*. 2001), overexploitation (Dichmont *et al*. 2003a), continued increases in fishing power (Dichmont *et al*. 2003b), or to the continued use of the now somewhat discredited MSY and E_{MSY} management targets (Larkin 1977; Punt *et al.* 2001).

Dichmont *et al.* (2001) undertook preliminary stock assessments of tiger prawns in the NPF at fine spatial scales. These assessments showed that some stock areas were much more depleted than the single-stock assessment would suggest. There was a need to clarify which stock areas are most affected, and why these stock areas were performing so poorly. There was also a need to develop a multi-stock operating model to open a new direction for modelling in the NPF. This technically complex model would have the potential to benefit the management of benthic crustacean species worldwide.

Given the Australian Fisheries Management Authority's (AFMA's) requirement to satisfy its ESD objective, there was therefore a need to consider uncertainty explicitly and to identify assessment methods and harvest strategies for short-lived species that are as robust as possible to incorrect structural assumptions and errors caused by limited data. Most importantly, these assessment methods and harvest strategies needed to be developed in the context of spatially-explicit considerations and a management system based on input controls.

A Management Strategy Evaluation framework is developed to examine the effects of the spatial scale, the temporal scale, and the overall complexity of tiger prawn assessment models on the ability to provide appropriate management advice. In addition, the framework is used to compare several alternative Management Strategies. A multi-species and multi-stock model is constructed and used to represent the "true" resource (this model forms the main part of what is known as the operating model). An operating model based on a 5-stock, two-species, tiger prawn resource forms the basis for the evaluations. The structure of the tiger prawn resource is based on expert opinion of stock number and boundaries (Dichmont *et al.* 2001) and by estimating the values of model parameters using historical stock and species-group level logbook data (analysed separately to species level). Banana prawns are represented in the operating model by assuming that historical catch levels reflect the best appraisal of future catches. No stock-recruitment relationship is assumed for banana prawns, although preliminary studies suggest that one may exist (Vance *et al.* 2003).

The annual steps in the operating model are an automated representation of the present management system:

1. a tiger prawn assessment is undertaken every year;

2. the optimal effort and season length for achieving the target reference points for the fishery are recommended by the Northern Prawn Fishery Assessment Group based on this assessment; and
3. AFMA (on the advice of NORMAC) set the season dates and total effort level.

Historically, management action has been heavily biased towards the *status quo*; when fishing effort has been reduced, this has been implemented through changing the length of the season, reducing the number of fishing vessels, or reducing the amount of gear available for fishing.

Sources of uncertainty and error are explicitly included in the evaluations of this study, again based on past experience. These sources include:

1. errors or biases in the effort data used in stock assessments, caused by uncertainties in the process of splitting species-aggregated effort into effort by species;
2. biases or error in the results of assessments caused by inaccuracies in the key assumptions required, for example, assuming a single stock or incorrect values for model parameters (e.g. fishing power, catchability, etc.);
3. high levels of inertia on the part of management; and
4. implementation error when imposing management decisions - in this study, this source of uncertainty is assumed to relate only to the total level of fishing effort rather than the dates for the fishing season (VMS is good at detecting deviations from the latter). In the past, "implementation errors" led to the effect of a reduction in effort being much more *or* less than that intended.

Modelling the management system involved specifying formal decision rules to mimic the way management decisions are made, even though this fishery does not currently use decision rules.

Management strategies consist of an assessment procedure combined with a set of decision rules to determine the total tiger prawn effort levels each year. Three alternative assessment procedures are examined and compared:

1. a running 5-year linear regression of recent catch rates;
2. a biomass dynamic model that assumes a single-stock and operates on a annual time-step; and

3. a species-specific Deriso model with a weekly time-step (this model can be applied to the entire resource or in a multi-stock model).

Performance measures are developed to compare the risk to the resource and the economic performance of the fishery when different combinations of assessment procedure, decision rules and specifications for the operating model are considered. Furthermore, the ability to estimate key output quantities (estimates of parameters and management-related quantities) are quantified and presented.

Several performance measures are used. Many of the risk-related performance measures are defined relative to the spawning stock size corresponding to Maximum Sustainable Yield (S_{MSY}) because the NPF currently uses S_{MSY} as a Limit Reference Point (LRP); in fact, the LRP for the NPF is that there is a probability of more than 70% that the resource is above S_{MSY}. For ease of calculation, this project used the median of the S_{MSY} estimates as the LRP (i.e. 50%). Fishery stability is quantified through economic performance measures such as catch variability, long term catch (discounted at 5% per annum as suggested by economists, Kompas *pers commn*), the lowest catch during the projection period, and the probability of total tiger prawn catches falling below 2000t (seen as a very poor year).

Factors affecting Management Performance

An exploratory set of simulations is undertaken to evaluate the management system and to identify the key factors impacting performance. A statistically unbalanced design had to be used in this exploratory phase because a fully balanced design would have been computationally prohibitive. The key factors affecting performance were identified to be:

1. fishing power;
2. catchability; and
3. fishing power and catchability combined.

Factors found to be of lesser importance were:

1. the amount of implementation error;
2. whether recruitment is spatially correlated among stocks or not;
3. the method of capturing parameter uncertainty; and
4. error when compiling and summarizing the data used for assessment purposes.

These seven factors formed the basis for a subsequent balanced design of scenario runs.

Many of the management strategies based on the Deriso assessment procedure tend to leave the spawning stock size of *P. esculentus* below the target level of S_{MSY} in median terms. A case therefore could be made for choosing one of the more conservative management strategies; at least until a management strategy is developed that is better able to leave the spawning stock size of *P. esculentus* above S_{MSY}. There were two time series of fishing power termed the Base Case High and the Base Case Low, which bounded the range of possibilities that came from a detailed investigation of fishing power changes through time (Dichmont *et al.* 2003). Setting the fishing power series to Base Case High leads to more conservative management advice than setting the fishing power series to Base Case Low. The catchability is a parameter whose value is specified and not estimated. Two alternative values were used, the first as ”q” (Wang 1999) and the second as twice “q”, that is “2q”. Of the management strategies based on the Base Case High fishing power series, that based on setting catchability to “2q” in the assessment is more conservative than that based on setting catchability to “q”, although the difference is slight, at least compared to the impact of the choice of the fishing power series.

Care should be taken that the data have enough information to estimate stock size *and* catchability (if catchability is estimated within the assessment, as is the case for the biomass dynamic model). At present, only logbook data are available for assessment purposes and it seems unlikely that there is enough contrast in stock size and exploitation rate to estimate both stock size and catchability without serious bias and model instability. The new recruitment surveys in this fishery have the potential to provide the data required to estimate the values for parameters such as catchability, in contrast to the present situation where these values are either assumed and pre-specified (as is the case for the Deriso model) or estimated with low accuracy (as is the case for the biomass dynamic model).

Given the possibility of pre-specifying catchability at an incorrect value, it was necessary that performance indicators from stock assessments should focus on the ratio of the spawning stock size in a given year relative to, say, S_{MSY} or the spawning stock size that would achieve Maximum Economic Yield, S_{MEY}, rather than on effort, catch or spawning stock size in absolute terms.

The economic performance of the fishery can be severely compromised by implementation error. Hence reducing the degree of implementation error as much as possible should become a high management priority; historically it has been of the order of 18%.

Model complexity and scale

The influence of the temporal scale, the spatial scale, and the overall complexity of the assessment procedure on the performance measures is investigated. The ideal is to be able to use a simple assessment procedure and set of decision rules that is nevertheless able to achieve the management objectives for the fishery.

The difference between a target reference point (TRP) and a limit reference point (LRP) is important. The TRP is assumed to be the ideal state for the fishery (where the balance between long-term productivity and sustainability is optimized; see Caddy and Mahon 1995). On the other hand, the LRP is an agreed upon threshold state beyond which a fishery requires immediate and strong management measures to move the stock and fishery back towards the TRP. In the case of the NPF, the fishery moved in 2004 to using the Maximum Economic Yield (fixed to economic values determined in Rose and Kompas (2004)) as its TRP. However, this TRP is not considered in this thesis because it is not defined at the species level and because economic data were unavailable to the current project. It will, however, be used in a newly funded project where the Management Strategy Evaluation framework developed here will be expanded to include economic and ecosystem considerations.

Increasing the target spawning stock size used in the management strategy to define effort levels leads to higher spawning stock sizes (less risk) but lower catches (less reward). However, there is some non-linearity in the relationship between decreasing risk and decreasing reward. If the target spawning stock size used in the management strategy to define effort levels is increased from S_{MSY} to 1.2 S_{MSY} there is only a relatively minor loss in catch. However, as this target spawning stock size is increased above 1.2 S_{MSY} the reduction in catch grows disproportionately. When the target spawning stock size used in the management strategy is 1.6 S_{MSY} the lowest catch during the projection period is close to 1000t per annum and the median discounted catch is only about 70% of that when the target spawning stock size in the management strategy is S_{MSY}. The non-linearity of these effects implies that the benefits of increasing the target spawning stock size used in the management strategy to slightly above S_{MSY} seem to exceed the costs. Catch rates would be higher if the stock size is higher, and this would be expected to offset the economic costs of reduced catches to some extent. However, in the absence of detailed information about costs available to this study, the size of the offset cannot be quantified precisely.

None of the management strategies are able to stabilize the spawning stock size of *P. esculentus* (particularly that in Karumba stock area) at S_{MSY} if they set the target spawning stock size used in the management strategy to S_{MSY} even when the assessment model is based on the most of the same assumptions as the operating model. Trying to account for stock structure by applying the assessment procedure to parts of the NPF (i.e. by conducting a spatially-structured assessment) did not resolve this problem, probably because, even if assessments are conducted spatially, there remain no restrictions on where in the NPF fishing is to occur. Since some stock areas have much higher abundances in absolute terms, and are consequently almost always fished, effort remains in those stock areas irrespective of their stock status and much higher effort moves to those stock areas than is required to leave the spawning stock size at (or above) S_{MSY}. Even reducing the total effort (by increasing the target level of spawning stock size in the decision rule) does not achieve the desired goal of reducing effort in stock areas such as Karumba and Mornington.

The estimates of S_Y/S_{MSY} from the Deriso model-based assessment are fairly accurate for *P. esculentus* when the assumptions about catchability and fishing power series made when conducting the assessment are similar to those on which the operating model is based. This implies that the inability to leave the spawning stock size of *P. esculentus* at (or above) S_{MSY} is not related primarily to inadequate assessments. Rather, this poor performance is probably due to inadequacies in the decision rules, either because the wrong season length is set or because the spatial allocation of fishing effort is unrestricted. In contrast to the case of *P. esculentus*, the estimates of spawning stock size for *P. semisulcatus* (and hence S_Y/S_{MSY}) provided by the Deriso model-based assessment procedure are biased. This bias does not, however, prevent management strategies based on this assessment procedure from leaving the spawning stock size of *P. semisulcatus* at S_{MSY} on average.

Changing the algorithm that specifies season length in the management strategy was examined, but, unless the method used to specify the total effort is also changed, modifying this algorithm to avoid catching *P. esculentus* simply leads to a reduction in size of the *P.*

semisulcatus spawning stock. Increasing management's responsiveness to scientific management advice by changing the season length *and* total effort when this is recommended by the management strategy did not improve performance. This result further demonstrates that it is the inability of management to influence the spatial distribution of effort that is the main reason for the poor performance.

It seems clear therefore that some form of spatial management will eventually be required to ensure that all stocks for both species are at or above S_{MSY}. This in turn may necessitate spatially-structured stock assessments. If it becomes necessary to undertake such assessments, it seems appropriate to select a spatial structure that allows results for the Weipa and Karumba stock areas to be obtained separately. However, although spatially-structured assessments may reduce the bias caused by applying an assessment procedure to data for several stocks simultaneously, it should be understood that a spatially-structured assessment could have higher levels of uncertainty attached to the outcomes, (a) because it needs to estimate more parameters from the same amount of data and (b) because stock boundaries, if they exist objectively at all, are poorly known with those presently used for this study based only on expert opinion. Other concerns associated with moving to a spatially-structured stock assessment relate to the true number of stocks and the implications of movement among putative stocks. If spatial management is impossible to implement the only way to ensure that the spawning stock size is at or above S_{MSY} for both species is to undertake a mixture of a short first season (or no tiger prawn fishing) and a conservative target spawning stock size for brown tiger prawns in the decision rule.

Despite moving to MEY as the TRP, it seems likely that management will continue to want estimates of management-related quantities such as spawning stock size relative to S_{MSY}. Therefore, any future management recommendations would have to be based, to some extent, on an approach which involves stock assessment of some sort. Of the two stock assessment procedures considered in this study, there seems little reason not to continue using the Deriso model-based assessment technique. Being the *status quo* is one advantage, but it has also become clear that without imposing additional constraints, the alternative stock assessment procedure (the biomass dynamic model) could become very unstable.

In principle, a reduction in the resources needed to conduct the assessment could be achieved without seriously compromising the management objectives if formal assessments are conducted every few (2-3) years and the cpue regression approach used to provide management advice for the intervening years. This option has yet to be fully evaluated using the MSE framework and the benefits of going this route may be minor because assembling the data tends to be the most time consuming task when conducting an assessment.

In conclusion therefore it would seem that movement towards spatially-structured assessments and management is appropriate. This entails a judicious compromise between model scale and complexity yet to be determined. However changing the *ad hoc* way the fishery is currently managed to one in which the approaches used to determine effort levels and season length are clear to all is an essential ingredient of this process.

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